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Multimodal Perception and Multicriterion Control of Nested Systems:

II. Constraints on Crew Members During Space Vehicle Abort, Entry, and Landing

P. Vernon McDonald, Gary E. Riccio, Gregg E. Irvin, and Jacob J. Bloomberg

April 1998

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Acronyms

A/L	approach/landing
ADI	attitude director indicator
AMI	alpha/Mach indicator
BFS	backup flight system
CRT	cathode ray tube
CSS	control stick steering
DOF	degrees of freedom
ET	external tank
GN&C	guidance, navigation, and control
HUD	head-up display
ISS	International Space Station
LCD	liquid crystal display
MECO	main engine cut off
MEDS	multifunctional electronic display system
PASS	primary avionics software system
PIO	pilot-induced oscillation
SPI	surface position indicator
SRB	solid rocket booster
TAEM	terminal area energy management
VOR	vestibulo-ocular reflex

Preface

This series of three reports will describe the challenges to human perception and motor control that result from whole-body perturbations during locomotion. Our approach to this set of problems is based on the assumption that individuals, in the context of their surroundings, are adaptive nonlinear control systems with multiple levels of nesting, multiple inputs, and multiple outputs. We consider interactions between individuals and their surroundings to be the fundamental unit of analysis for research in human perception and movement. Our approach to the analysis of nested biological control systems was developed over more than a decade of research on human-machine interactions in aerospace operations. The early research was conducted in collaboration with the Air Force Armstrong Laboratory at Wright-Patterson Air Force Base, Ohio (see e.g., Brown, Cardullo, McMillan, Riccio & Sinacori, 1991; Riccio, 1993; Zacharias, Warren & Riccio, 1986). Recent research also includes collaboration with the Neuroscience Laboratory at the NASA Johnson Space Center in Houston, Texas (see e.g., Riccio, McDonald, Peters, Layne & Bloomberg, 1997).

The first report in the series, "Multimodal Perception and Multicriterion Control of Nested Systems: I. Coordination of Postural Control and Vehicular Control," describes the theoretical and operational foundations for our analysis of human-environment interactions. This report focuses on the coupled biological control systems involved in piloting an air vehicle and in stabilizing perception and movement in the cockpit. It is emphasized that the analysis is not limited to vehicular control. The analysis is presented in a way that is generalized to all forms of locomotion and to other activities that involve whole-body perturbations. In addition, the report motivates and facilitates comparisons between conditions of real and simulated vehicular motion. This provides a framework for assessing human perception and performance in real-world conditions, in controlled conditions that allow for more refined measurement and evaluation, and in simulations that are intended to foster the development of skill.

The second report in the series, "Multimodal Perception and Multicriterion Control of Nested Systems: II. Constraints on Crew Members During Space Vehicle Abort, Entry, and Landing," applies our theoretical framework for nested human-environment interactions to the problems of flight crew perception and performance during planned and potential aerodynamic maneuvers of space vehicles. This report presents an approach to identification of task demands on perceptual and motor systems on the flight deck, to the measurement of perturbations to and interactions among the various subsystems of the human body, to the assessment of the skills involved in coordinating the nested subsystems in the presence of such disturbances, and to the development of flight deck displays and controls that promote such skill and that increase robustness of the human-machine system.

The third report in the series, "Multimodal Perception and Multicriterion Control of Nested Systems: III. Assessment of Visual Stability During Treadmill Locomotion," applies our theoretical framework to the problem of eye-head-trunk coordination during walking or running. This report presents a method for evaluating visual resolution and gaze stability during common activities involving whole-body motion. The functional visual assessment test that is described provides a measure of visual "acuity" that is sensitive to coordination between the oculomotor subsystems and other biomechanical subsystems of the body. This approach enhances diagnostic sensitivity to a variety of physiological impairments, and it enhances diagnostic relevance with respect to operational or everyday activities.

Abstract

This report reviews the operational demands made of a Shuttle pilot or commander within the context of a proven empirical methodology for describing human sensorimotor performance and whole-body coordination in mechanically and perceptually complex environments. The conclusions of this review pertain to

a) methods for improving our understanding of the psychophysics and biomechanics of visual/manual control and whole-body coordination in space vehicle cockpits.

b) the application of scientific knowledge about human perception and performance in dynamic inertial conditions to the development of technology, procedures, and training for personnel in space vehicle cockpits.

c) recommendations for mitigation of safety and reliability concerns about human performance in space vehicle cockpits.

d) in-flight evaluation of flight crew performance during nominal and off-nominal launch and reentry scenarios.

1. Identification and Significance of the Issues

In this report we review the factors that affect the stability and adaptability of flight crew visual and manual performance during space vehicle launch, reentry, and landing maneuvers. The operational relevance of these effects are specified in terms of the implications for current and advanced cockpit design.

A large proportion of the information the crew monitors in the current Orbiter cockpit is visual. At the same time, the crew accomplishes the majority of its control inputs manually. As in other vehicles, maintenance of visual stability and manual stability is a fundamental component of piloting skill. Visual and manual stability are complicated by postural perturbations that result from controlled maneuvers and uncontrolled disturbances of the space vehicle during ascent and descent. Consequently, three related behavioral goals are to stabilize gaze for visual acuity, stabilize the hand for manual control, and control the nested eye-head-torso-arm-hand system in the presence of mechanical disturbances. Moreover, at the time of atmosphere reentry, the crew may be adapted to weightlessness while they must function reliably in a rapidly changing inertial environment. Whole-body coordination must be sufficiently adaptable to ensure stability of the visual and manual subsystems given such challenging conditions. The Shuttle pilot and commander must be prepared for the following specific challenges:

- Both the sensory and musculoskeletal systems are affected by weightlessness. The severity of the aftereffects that can be detected immediately postflight depend on the amount of time spent in weightlessness.
- The reentry phase of a mission is characterized by a rapidly changing inertial environment. Nominal Shuttle reentry entails varying g-loads up to 1.5g (nominally through the z-axis) occurring immediately following the transition from weightlessness.
- Launch abort scenarios (e.g., East Coast Abort) will entail rapidly changing g-loads deviating from the +3g acceleration of a nominal Shuttle launch.

- Buffeting as a result of variations in the air mass causes vibration of the airframe and the operators during entry and landing.
- Transient disturbances (e.g. wind gusts) can occur unexpectedly during the entry and landing.
- The opportunities for breaking off a particular flight procedure are either nonexistent or rapidly diminishing irrespective of the challenges that are encountered during abort, entry, or landing. There is not a second chance.

We believe that crew effectiveness in these scenarios must be addressed for a number of reasons, including the following:

- NASA-sponsored research has shown that control of the eyes, head, and trunk is compromised by the aftereffects of weightlessness. The task-relevant consequences of such aftereffects include, for example, significant changes in visual performance immediately postflight.
- NASA-sponsored research is providing increasing evidence of changes in human perception and performance following short- and long-duration space flight. Depending on the length of the flight these effects can be severe.
- Research conducted outside of NASA indicates that whole-body coordination is compromised by levels of variation in the inertial environment that are within nominal parameters for Shuttle entry and landing.
- Research conducted outside of NASA indicates whole body coordination is compromised by levels of vehicular vibration that are within nominal parameters for Shuttle entry and landing. There is clear evidence that human perception and performance in aircraft cockpits is affected by vibration and other environmental stressors to the extent that whole-body coordination is compromised.
- There is a notable lack of information about the capabilities and limitations of whole-body coordination on the flight decks of space vehicles, especially in off-nominal reentry and landing conditions.
- There is a notable lack of information about the operational robustness of human perception and performance on the flight decks of space vehicles during off-nominal scenarios.

Visual and manual stability during space vehicle launch/reentry/landing is important for the detection of deviations from nominal flight conditions and for the timely and reliable execution of actions that are appropriate for any off-nominal conditions. Decisions will be made with less confidence and will be delayed when circumstances degrade *visual* performance. Similarly, control responses may be inaccurate and delayed when circumstances degrade *manual* performance. In this report we evaluate the nature and extent of changes in visual and manual performance due to the aftereffects of weightlessness, the effects of aero disturbances, and the effects of a variable-g environment. Our intent is to evaluate these effects in the specific context of flight deck operations so as to determine the implications for design of flight deck technology.

Our review will focus on visual/manual control and on the timeliness and confidence of the attendant decisions. It also will relate indirectly to the adaptability and stability of the pilots' more-or-less continuous flight control actions. We have shown that results from conventional psychophysical studies of sensory systems can help explain characteristics of manual control and sensorimotor integration observed in simulated aircraft (Flach, Riccio, McMillan, & Warren, 1986; Riccio & Cress, 1986; Zacharias, Warren & Riccio, 1986). Such research is important because, in the atmosphere, the Shuttle operates like a conventional aircraft in a low lift/drag approach (Berry, Powers, Szalai, & Wilson, 1982). The rotational hand controller controls the elevons for pitch and roll, and pedals control the rudder for yaw.

Control of a vehicle and control of the pilot-vehicle system depends on the characteristics of the human sensory systems as well as the characteristics of the human motor systems. Visual stability and resolution, for example, are important during the various phases of landing (e.g. heading alignment, flare, and touchdown) insofar as it influences pilot workload and handling qualities (Berry et al., 1982; Smith & Bailey, 1982; Weingarten, 1978, 1979). As with damage to the Shuttle's structure or flight-control systems, *impairment of the pilot's sensory or motor systems can lead to degraded flying qualities*, pilot-induced oscillations (PIOs) and catastrophic failure. It is important to note that degradation in handling qualities and flight-control performance is highly nonlinear or "explosive" over smooth changes in parameters of the pilot-vehicle system (Smith & Bailey, 1982). This quantitative finding is reinforced by pilot comments: "an unsatisfactory or worse flight control system can look benign until taxed near the limit" (Berry et al., 1982, p. 323). These qualitative and quantitative characteristics have been noted since the initial test and evaluation of Shuttle Orbiter landing (e.g., Weingarten, 1978, 1979). It follows that *problems with off-nominal conditions may not be predicted from behavior observed under nominal conditions* unless one more closely examines the human subsystems involved in control of the pilot-vehicle system (Riccio, 1995; Riccio et al., 1998).

There have been occasions where Shuttle flight crew have made direct reference to visual problems during reentry and landing. Such comments have been made to the authors of this report, to a member of the NASA Johnson Space Center (JSC) Advanced Orbiter Cockpit team, and to engineers in the JSC Structures and Mechanics Division. To date these comments have been informal observations, but the JSC Advanced Orbiter Cockpit team is currently surveying all the active flight crew for their opinions pertaining to the human interface of current Shuttle flight deck displays and controls especially with reference to launch, ascent, reentry, and landing. Finally, at least one Shuttle commander is firmly convinced that there is no way he could land the Shuttle after a long-duration flight (>1 month) given the adaptive effects of long-duration flight.

Understanding crew effectiveness has direct implications for space vehicle design. The future Shuttle flight deck will incorporate new display and control technology that improves crew effectiveness to the extent that constraints on human perception and performance are addressed during design. Orbiter upgrade efforts that increase flight crew autonomy and situational awareness could correspondingly increase the reliance on human perception and performance. Any effort to increase flight crew situational awareness will rely on accurate perception of system status through flight deck displays and controls. In the near future, we will have crews flying on the International Space Station (ISS). ISS emergency evacuation will require that crew members pilot a crew return vehicle after having spent up to several months in weightlessness. The ISS crew return vehicle currently is being designed. Finally, successful landing of a manned spacecraft during future missions to Mars will depend on the capabilities of a human operator who has spent 6 months or more in weightlessness.

2. Shuttle Flight Deck Operations and Conditions

2.1 Visual and Manual Demands on the Flight Deck

This section presents material for the purpose of evaluating task demands on visual and manual control in the flight deck of extant and planned space vehicles. Knowing the exact nature of the flight crew responsibilities is critical to display and control design and accurate evaluation of the relevance of physiological and environmental factors.

A characteristic activity of the Shuttle pilot and commander during reentry and landing is to monitor multiple instruments and displays that are spatially distributed over the flight deck console (Fig. 1). The spatial distribution of manual controls is such that, even in a nominal reentry, a “stick” must be used to reach certain switches. Such spatially distributed manual and visual tasks are complicated by postural perturbations that result from controlled maneuvers and uncontrolled disturbances of the Shuttle during ascent and descent. Consequently everything from postural control in the cockpit to looking and reaching patterns must be considered as part of a pilot’s *skill*. This skill allows a pilot to perform effectively in the visually and mechanically complex aerospace environment. *Adaptability* is an essential aspect of such whole-body skills, and it allows a pilot to perform adequately even in novel or unusual circumstances. The design of controls and displays and the development of flight-control procedures takes into account, explicitly or implicitly, such skill and adaptability. Planning for new environments or emergency situations is greatly facilitated by a technical understanding of the limits of human skill and adaptability.

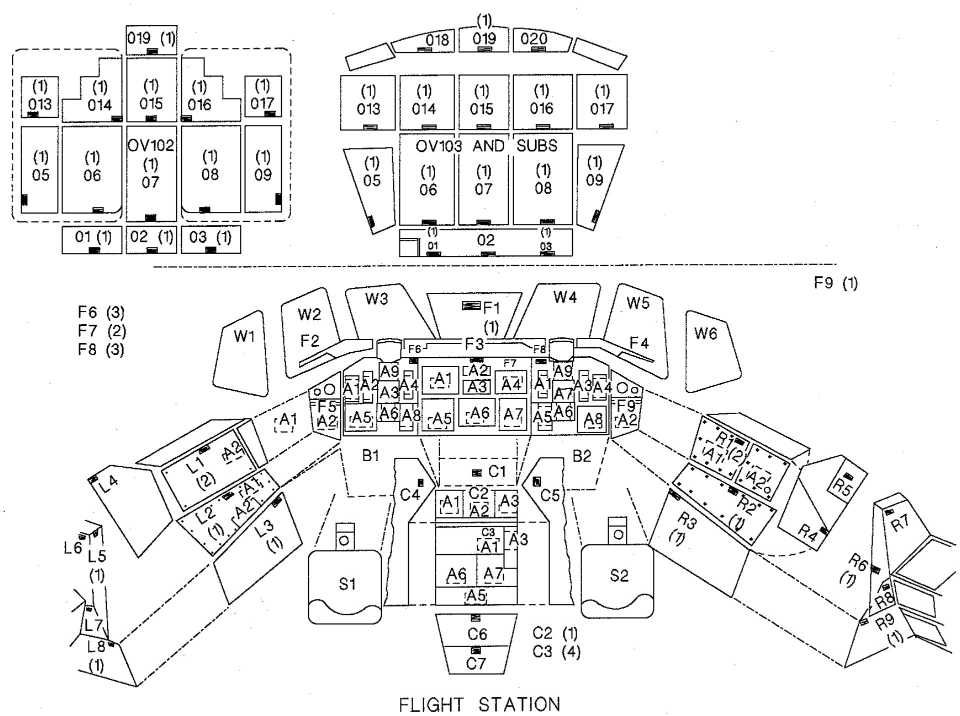

Figure 1. Schematic showing panel identification for current Shuttle flight deck controls and displays. Seats are shown as S1, S2; windows are shown as W1-W6; overhead panels are shown as O1-O20.

The extent of the Shuttle flight deck reach and visibility problem is best explained in the following excerpt from document JSC-12770, “Shuttle Flight Operations Manual,” Mission Operations Directorate Training Division, 1985 (3.28, Visibility and Reach Provisions: 3.28.1 Introduction):

> Visibility and reach provisions are those hardware items necessary to allow the crew to see/actuate essential displays and controls (D&C) while restrained in their seats during critical flight phases. These provisions include the reach aid, the adjustable mirrors, and the wicket tabs. The reach aid (sometimes known as the ‘swizzle stick’) is a short bar that is used to actuate controls that are out of reach of the seated crew member (figures 3.28-1 and 3.28-2). The two-axis adjustments of the Commander (CDR) and Pilot (PLT) operational seats (sec. 3.4) is also intended to make controls more accessible.
>
> Two adjustable mirrors provide rear and side visibility to the CDR and PLT for assessing separation of the external tank from the Orbiter and for checking D&C and man/seat interfaces (fig 3.28-3). Fields of view through the flight deck windows are shown in figure 3.28-5. Vision restrictions are usually more severe than reach restrictions; therefore, certain switches will be operated in the blind (by feel) if necessary. Wicket tabs have been developed to aid the crew in the operation of controls by touch (fig 3.28-4). The wicket tabs may be used as reference points for actuating controls, permitting visual freedom for concentrating on other flight phases.
>
> It is important to note the full meaning of the words ‘see’ and ‘actuate’ when discussing the crew member-control interface on the Orbiter. ‘See’ defines the ability of the crew member to read nomenclature on the controls, discern the positions of circuit breakers, and toggle switches, read numbers on rotary detent switches and CRT [cathode ray tube] displays, discern colors on warning lights, read gauges, and determine if particular lights are on or off. ‘Actuate’ refers to the ability of the crew member to flip toggle switches, turn knobs, pull circuit breakers, push detent buttons, and make manual inputs into CRT keysets and other related controls. Both ‘see’ and ‘actuate’ refer directly to the vision and reach envelopes of the crew member at his crew station during particular phases of flight.
>
> The limitations of the CDRs and PLTs reach and vision envelopes are functions of the crew members’ anthropometry, helmet, seat adjustability, seat back angle, Orbiter orientation, and acceleration forces. The reach and vision limitations in table 3.28-1 and in figures 3.28-6 through 3.28-11 describe envelopes (without the reach aid) determined in a JSC mockup review of NASA astronauts wearing flight suits. It should be understood that this study was done in a 1g situation, and therefore is only a simulated measure of launch g-loading. Furthermore, the definition of ‘see’ and ‘actuate’ were not rigorously enforced throughout the test. Discretion should be used interpreting these results and applying them to real-time Shuttle reach and vision envelopes for ascent loads over 1.5g. Reach envelopes in figures 3.28-6 through 3.28-11 are omitted where there are no limitations.

JSC-12770 indicates that, during powered ascent (>2gx), only 12 panels of 30 are fully accessible from the Pilot/Commander positions. A full 60% of the panels therefore are either partially or totally inaccessible during this mission phase.

Manual control in the Shuttle flight deck is a combination of discrete (e.g. turning a switch) and continuous (e.g. controlling the stick) activities. The continuous activities tend to be confined to a specific location in the reach envelope. However, the discrete activities can be distributed anterior, posterior, lateral, superior, and inferior to the shoulder. The reach envelopes of astronaut pilots, and the associated postural configurations, have been rigorously evaluated in relation to flight-deck displays and controls and under a variety of typical g-loads (Bagian et al., 1993). Such data have important design implications, some of which are not obvious without an understanding of the whole-body involvement in visual and manual control. For example, the postural configuration required to support a manual task is critical in determining how vibration is transmitted through the body to the hand (Levison & Harrah, 1977). It is reasonable to propose therefore that the spatial distribution of manual tasks can be optimized so as to avoid those postures most susceptible to vibration. How manual performance is compromised by vibration will also depend on the resistance to motion offered by the controlled device, as well as the control dimension of the device (displacement, force, velocity, etc.).

No guidance, navigation, and control (GN&C)-related crew actions are planned for first stage of ascent unless a failure occurs. To ensure that the auto flight control system is maintaining the expected ascent profile, the flight crew can verify that the vehicle is at the correct pitch attitude (via the attitude director indicator) and altitude rate (via the altitude/vertical velocity indicator) at each of five designated times during first-stage ascent. The flight crew can monitor that the main engines correctly throttle down and up. They can also ensure that the Pc-50 message (chamber pressure greater than 50 psi) correctly appears on the major mode 102 (first-stage) ascent trajectory CRT display before solid rocket booster (SRB) separation and that SRB separation occurs on time. *Manual intervention by the crew is required if these events are not automatically accomplished*. The crew is also responsible for monitoring main engine performance. During first-stage ascent, only limited information is available to the crew on the primary avionics software system (PASS) and backup flight system major mode 102 displays.

During second-stage ascent, the flight crew monitors the onboard systems to ensure that the major GN&C events occur correctly and on time. These events include closed-loop guidance convergence, 3-g throttling, main engine cut off (MECO), external tank (ET) separation and the negative Z translation following ET separation. To monitor these events, the flight crew uses the dedicated displays: the main engine status lights on panel F7 and the PASS ascent trajectory and the bakcup flight system (BFS) ascent trajectory 2 displays.

The crew can monitor guidance convergence by noting if the guidance-computed time of MECO is stabilized on the ascent trajectory display. If not, the crew takes manual control of the vehicle. They can also ensure that acceleration does not exceed 3 g's via the BFS ascent trajectory 2 display as well as the accel tape on the alpha/Mach indicator (AMI). The crew can monitor MECO velocity on the BFS ascent trajectory 2 display as well as on the M/vel tape on the AMI. MECO is detected by the illumination of three red main engine status lights and by the main propulsion system chamber pressure meters on panel F7 going to zero.

Depending on mission requirements, the crew may be required to translate in the plus X direction, using the translational hand controller for 11 seconds, to allow the ET camera to photograph the tank.

At specified points during second-stage ascent, the Mission Control Center will make voice calls to the crew indicating their status with respect to aborts. For example, the "negative return" call indicates that it is too late to select a return-to-launch-site abort.

During landing, in the automatic mode, the Orbiter is essentially a missile, and the flight crew monitors the instruments to verify that the vehicle is following the correct trajectory. The onboard computers execute the flight control laws (equations). *If the vehicle diverges from the trajectory, the crew can take over at any time by switching to control stick steering* (CSS). The Orbiter can fly to a landing in the automatic mode (only landing gear extension and braking action on the runway are required by the flight crew). The autoland mode capability of the Orbiter is used by the crew usually to a predetermined point in flying around the heading alignment cylinder. In flights to date, the crew has switched to CSS when the Orbiter is subsonic.

About five minutes before entry interface, the crew adjusts the software to major mode 304. During this mode, which lasts until terminal area energy management (TAEM) interface, five CRTs become available sequentially and are used to monitor auto guidance and the Orbiter trajectory compared to the planned entry profile. The five displays are identical except for the central plot, which shows the Orbiter's velocity versus range or energy/weight versus range with a changing scale as the Orbiter approaches the landing site. This plot also includes static background lines that allow the crew to monitor the Orbiter's progression compared to planned entry profiles.

Once TAEM interface is reached, the software automatically makes a transition to major mode 305. The CRT vertical situation 1 display then becomes available. It includes a central plot of Orbiter altitude with respect to range. This plot has three background lines that represent the nominal altitude versus range profile, a dynamic pressure limit in guidance profile and a maximum lift-over-drag profile. At 30,000 feet, the scale and title on the display change to vertical situation 2, and the display is used through landing. When the approach and landing interface conditions are met, a flashing "A/L" appears on the display.

Another prime CRT display used during entry is the horizontal situation. In addition to providing insight into and control over navigation parameters, this display gives the crew Orbiter position and heading information once the Orbiter is below 200,000 feet.

The flight crew then uses the entry trajectory, vertical situation, and horizontal situation CRT displays to monitor the GN&C software. They crew can also use them to determine whether a manual takeover is required.

In summary, it is clear that human operations are integral to Shuttle flight control. While complex monitoring encompasses the majority of nominal launch and landing activities, there is the expectation that the crew can manually control the Shuttle, should it be necessary. Such off-nominal activities are more complex given the need for discrete and continuous manual control inputs in addition to complex visual monitoring.

2.2 Shuttle Launch/Reentry/Landing Conditions

This section presents material for the purpose of evaluating disturbances that are common during Shuttle launch & reentry. These include vibrations, transient disturbances, and changes in the g-loads.

Excerpts from NASA-STD-3000/Vol.1/Rev.B describe NASA's position on the launch and reentry environment, and vibration phenomena from a human performance perspective.

> Vibration seldom occurs in the operational situation as a single isolated variable. Other environmental variables such as weightlessness, linear acceleration, etc., can be expected to interact with vibration either to reduce or to increase the debilitating effects. Equipment variables include size of graduations or illumination of instruments, inflated pressure suits, etc.; procedural variables include task load, variations in time of performance, etc.; and finally, personal variables, such as fatigue and deconditioning. The effects of some of these can be predicted at this time; others must await further research....Studies of human response to vibration have been conducted in field environments and in complex laboratory simulations. However, most of the available information results from laboratory experiments. The most useful information shows the effects of changing the characteristics of vibration (magnitude, frequency, etc.), the influence of modifying the transmission of vibration to the body (by seating and postural alterations), the sources and extent of individual variability, and the effects of alterations to the operator's task. [Section 5.5.2 Vibration Design Consideration]

> Significant levels of vibration occur routinely in space module operations during the maximum aerodynamic pressure portion of boost. The vibration is coupled with a significant linear acceleration bias...The Mercury astronauts complained that vibration during boost interfered with their vision. The Titan II rocket produced intense vibration at 11Hz. [Section 5.5.2.1.1 Launch Phase Vibrations]

> Significant vibration levels occur during reentry but these levels are not as intense as experienced during the launch phase. The vibration is coupled with a significant linear deceleration bias... During entry, low-frequency oscillation may occur if entry angle is too steep. If the angle is more than one or two degrees, high peak oscillation, depending on the shape of the vehicle, may be produced. The frequency of such oscillations reach a peak coincident with the entry deceleration peak. The amplitude of the oscillation progressively decreases during deceleration. For an entry angle of ten degrees, a 2 Hz oscillation with a peak of 0.12-g and an arc of one degree has been predicted. Skip-glide entry of a lift-drag vehicle may produce oscillations. [Section 5.5.2.1.3 Entry Phase Vibrations]

> Vibration may affect crew member performance, and may produce physiological and biodynamic effects, as well as subjective or annoyance effects. Whole-body vibration may act additively with noise to cause stress and fatigue and degrade vigilance and performance. There has been limited research combining vibration with other environmental stressors such as acceleration, noise, and altitude. [Section 5.5.2.3 Human Responses to Vibration-Design Considerations]

> The physical responses of the body are primarily the result of the body acting as a complex system of masses, elasticities, dampings, and couplings in the low frequency range, i.e., up to 50 Hz. The impedance of the body and its parts and organs damp vibration over certain frequency ranges and may amplify vibration over other frequency ranges within various portions or all of the body. [Section 5.5.2.3.1 Physiological Effects of Vibration]

> Vibration affects performance either by modifying perception or by influencing control movements. [Section 5.5.2.3.2 Performance Effects of Vibration]

Notable in this material is the lack of detail in descriptions of the vibration environment, including the resulting postural perturbations, on the Shuttle flight deck during reentry. Data were collected on early Shuttle flights, but were directed more to evaluating structural integrity of the flight deck and instrumentation. Little or no attention appears to have been given to the human performance implications of these vibrations. However, some acknowledgment of these implications can be found in the "Shuttle Crew Operations Manual" (last update: August 1996). This document is provided as a reference for Space Shuttle crew members and contains information on each shuttle system and every phase of a generic Space Shuttle mission. Following are some specific items pertaining to sensations associated with Ascent and Entry:

> Prelaunch, SSME [Space Shuttle main engine] gimbal checks can be felt throughout the shuttle structure... First stage is characterized by a rapid g buildup to slightly over 2g, accompanied by a great deal of noise and vibration. Instruments and CRT displays can be monitored, but precise tasks are difficult. [7.1 Ascent: Sensory Cues]

> The digital auto pilot (DAP) includes bending filters in all axes that protect the DAP from coupling with the Orbiter structure in a resonant oscillation. If the bending filter constants were wrong, it could be possible to cause an oscillation...Symptoms are a high frequency oscillation (4 Hz), accompanied by airframe vibration caused by oscillation of the aero surfaces. The crew may observe these oscillations on the SPI [surface position indicator] or the ADI [attitude director indicator] rate needles. A yaw jet limit cycle may also occur. [7.3 Entry]

> Returning from orbit, some crew members have reported increased sensitivity to g as it builds during entry. One crew member observed that "when you hit a quarter g on entry, it seems like two g's in the T-38...Crew members should be aware that their ability to perform entry tasks may be degraded from that experienced in the SMS during training. Keep in mind that g's stay around 1.3 until Mach 2.5. [7.3 Entry: Sensory Cues]

On the recent STS-78 launch, NASA positioned a video camera on the flight deck to record the ascent. A review of this tape and the associated comments made by the pilot during the subsequent downlink indicate the nature of the disturbances from the powered ascent:

> Pilot: "Now we are in, obviously, first stage. Pretty bumpy ride, and you can feel the throttle down."
>
> CapCom: "…it sure does show the rough ride of the solids."
>
> Pilot: "Yeah, as you well know, it is a pretty impressive ride on those boosters."

Quantification of these phenomena can be seen in Figures 2, 3, and 4, which present data of actual ascent g-loads and vibrations. The y-axis of the Shuttle runs from wing tip to wing tip, the z-axis runs from the topside to the underside of the wings. The vibration data in Figures 3 and 4 were gathered from accelerometers located in the nose of the Shuttle. Unfortunately, we were unable to obtain similar detailed vibration data for reentry. Figure 5 depicts a simulated reentry g-load profile. Reentry flight deck vibrations were described by structural engineers at NASA as "relatively benign" compared to the launch vibrations. However, those same engineers did report that postflight conversations with Shuttle crew members revealed a heightened sensitivity to any vibration and acceleration.

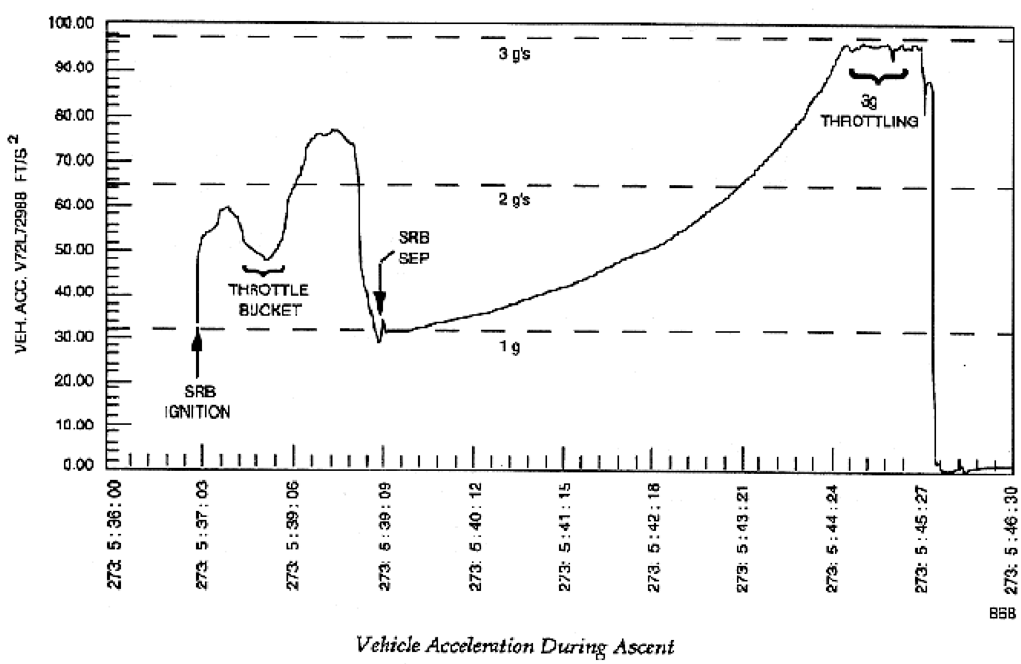

Figure 2. Typical Shuttle acceleration time history during ascent.

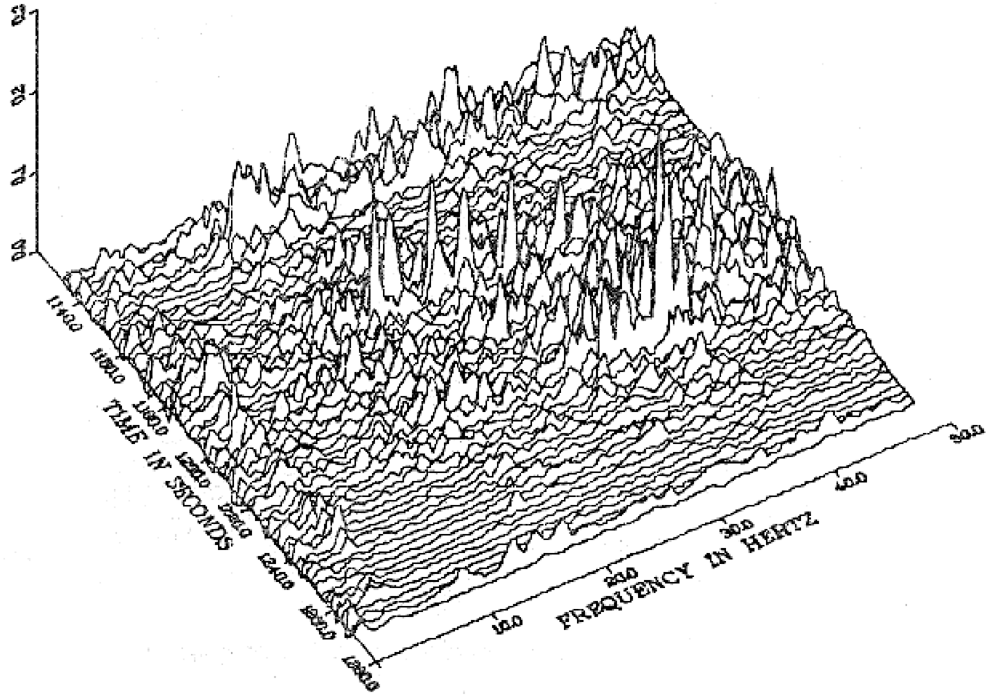

Figure 3. STS-5 flight deck y-axis vibration power spectra vs. time during ascent.

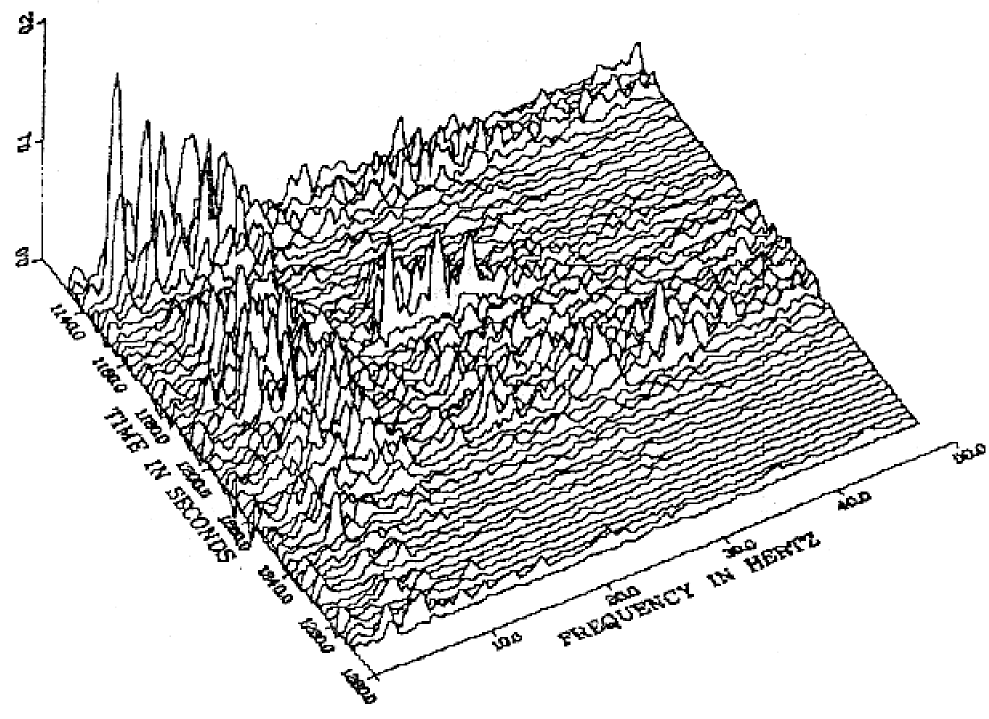

Figure 4. STS-5 flight deck z-axis vibration power spectra vs. time during ascent.

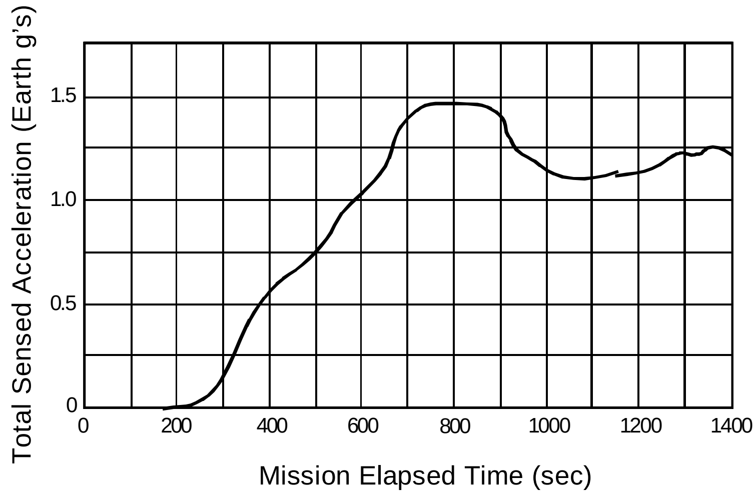

Figure 5. G-load vs. time for 3-DOF simulated reentry profile.

2.3 Current and New Technologies for Space Vehicle Flight Decks

On the basis of interactions with the Advanced Orbiter Cockpit program, we will evaluate the implications of human performance characteristics discussed above for current and proposed flight deck displays and controls.

2.3.1 Current Displays and Controls *(Adapted from the Shuttle Reference Manual)*

The crew compartment of the Orbiter contains the most complicated displays and controls ever developed for an aerodynamic vehicle. The displays and controls exist in a variety of configurations, with toggle, push button, thumbwheel, and rotary switches; and circular meters, rectangular dials, and rectangular tapes. Switches and circuit breakers are positioned in groups corresponding to their functions.

All controls are protected against inadvertent activation. Toggle switches are protected by wicket guards, and lever lock switches are used wherever inadvertent action would be detrimental to flight operations or could damage equipment. Cover guards are used on switches where inadvertent actuation would be irreversible.

The displays and controls in the Orbiter crew compartment enable the flight crew members to supervise, control, and monitor the Space Shuttle mission and vehicle. They include controllers, CRT displays and keyboards, coding and conversion electronics for instruments and controllers, lighting, timing devices, and a caution and warning system.

All displays and controls have dimmable floodlighting in addition to integral meter lighting.

There are more than 2,020 displays and controls in the forward and aft flight decks and middeck of the Orbiter. This represents more than 100 times the number of controls and displays found in the average automobile.

Orbiter displays and controls consist of panel displays, mechanical controls, and electrically operated controls. Generally, the displays and controls are grouped by function and arranged in operational sequence from left to right or top to bottom with the most critical and most frequently used devices located to maximize the crew's performance and efficiency.

The forward flight control area panels are labeled L for the left, or commander's position; R for the right, or pilot's position; F for the front section; O for the overhead position, and C for the lower center section (Fig. 1).

The head-up display (HUD) was introduced to the Shuttle to ease the demands on the fight crew, after HUD technology had proven so useful in military aircraft. The HUD is an optical miniprocessor that cues the commander and/or pilot during the final phase of entry and particularly in the final approach to the runway. With minimal movement of their eyes from the forward windows (head up) to the dedicated display instruments (head down), the commander and pilot can read data from HUDs located in front of them on their respective glareshields. The HUD displays the same data presented on several other instruments, including the ADI, SPI, AMI, and altitude/vertical velocity indicator.

The HUD allows out-of-the-window viewing by superimposing flight commands and information on a transparent combiner in the window's field of view. The baseline Orbiter, like most commercial aircraft, presents conventional electromechanical display on a panel beneath the glareshield, which necessitates that the flight crew look down for information and then up to see out the window. During critical flight phases, particularly approach and landing, this is not an easy task. In the Orbiter, with its unique vehicle dynamics and approach trajectories, this situation is even more difficult.

The current caution and warning system is worthy of note also. The system consists of software and electronics that provide the crew with visual and aural cues when a system exceeds predefined operating limits. Visual cues consist of four red *MASTER ALARM* lights, a 40-light array on panel F7, a 120-light array on panel R13U, and CRT messages. The aural cue is sent to the communications system for distribution to flight crew headsets or speaker boxes. Fault messages for some parameters are issued every time the software completes the required number of data counts with the parameter out of limits. This can result in a steady stream of fault messages and *MASTER ALARM*s that may obscure other important fault messages. If this situation is encountered, the crew or Mission Control can inhibit the affected parameter to prevent nuisance messages in alarms in OPS 2 or OPS 4. In OPS 1, OPS 6, or OPS 3 the crew generally has to tolerate the extra alarms/fault messages and pay extra close attention to the fault summary display.

2.3.2 Future Displays and Controls

One upgrade item already scheduled for integration into the Orbiter flight deck is the multifunctional electronic display system (MEDS). This upgrade will replace the current Orbiter cockpit displays, which are early 1970s technology. The current displays which provide command and control of the Space Shuttle are "single string" electromechanical devices that are experiencing life-related failures and are maintenance-intensive. The MEDS upgrade uses a state-of-the-art, multiple-redundant liquid crystal display (LCD) system to replace these devices. However, the MEDS system is intended to simply replicate the symbology and layout of the current displays. In essence, the MEDS LCDs will "draw" the displays so that they look identical to those currently used in the Shuttle.

Other efforts within NASA are addressing a complete overhaul of the Orbiter flight deck. The end result may have very little resemblance to today's Shuttle flight deck. In particular, efforts are under way to develop a state-of-the-art glass fight deck leveraged on the best "glass cockpit" implementations in the military and commercial sectors. Such a development would result in a reconfigurable flight deck in which only context relevant (e.g. ascent, orbit, reentry) displays and controls would be presented to the operator. One current working example of state-of-the-art flight deck technology, symbology, and architecture is seen in the Boeing 777. Reference for these upgrades include MIL-STD-1787B, "Aircraft Display Symbology," and AFGS-87213B, "Displays, Airborne, Electronically/Optically Generated."

Candidate technologies that have been considered to date include head down and head up displays, information display and symbology, information control technologies (e.g. hands-on throttle and stick), automation technologies, health monitoring, detection, and diagnosis implementations, and caution, advisory and warning implementations.

Find up-to-date information concerning advanced Orbiter cockpit concepts at the website of JSC's Rapid Prototyping and Interface Development Lab (http://dp4.jsc.nasa.gov:8001/PROJECTS/AOC/).

3. Human Perception and Performance

This section describes the effects of vehicular disturbances and the effects of adaptation to weightlessness on visual and manual performance in conditions that are relevant or comparable to Shuttle launch and reentry.

3.1 Effects of Whole-Body Perturbations on Visual and Manual Performance

Vibration and transients have consequences for nonrigid organisms in general (Riccio & Stoffregen, 1988) and, in particular, for occupants of vehicles who are neither rigid nor rigidly attached to the vehicle (Boff & Lincoln, 1988, pp. 2076-2081; Griffin, 1975; Riccio, 1995; Riccio et al., 1998). Because of the nonrigidity of the body and nonuniformities in the mass and moment of inertia of various body segments, relative motion of body segments is generated by the vibration and transients encountered during whole-body movement. Such disturbances can degrade vehicular control by interfering with perception and action in the cockpit. For example, movements of the head relative to the cockpit can degrade the pickup of information from instruments and displays (Boff & Lincoln, 1988, pp. 2082-2101; Griffin & Lewis, 1978; Lewis & Griffin, 1978; Moseley & Griffin, 1986). Uncontrolled body movements can also degrade manual control performance (Boff & Lincoln, 1988, pp. 2106-2117; Lewis & Griffin, 1978). A rich source of data on *transmissibility* of forces to the head and torso is the research on whole-body "vibration" of seated individuals (summarized in Boff and Lincoln 1988). There is a peak in transmissibility for both vertical and pitch motion of the head at vertical perturbation frequencies of 3-8 Hz (Fig. 6). At low frequencies, significant amounts of head motion can occur at the first harmonic of the vertical perturbation force. Transmission of vertical perturbations to the head has been shown to be affected by posture, muscle tension, body size, sustained acceleration, and attachment of extra masses (Griffin 1975), and by adaptation to space flight (McDonald et al., 1996).

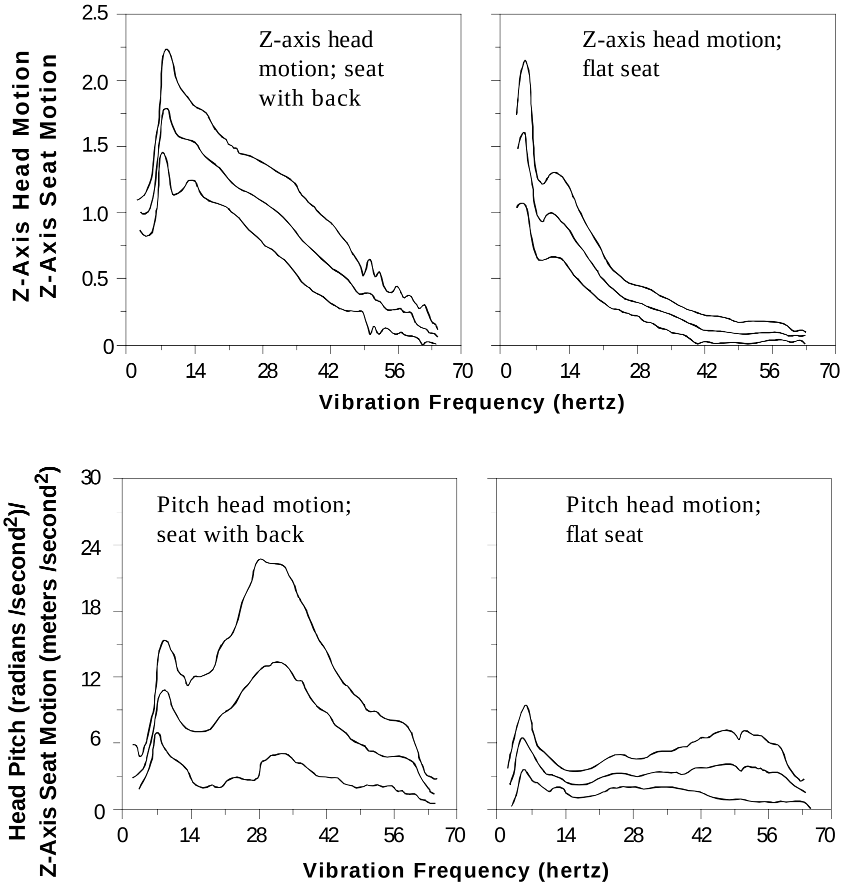

Figure 6. Transmissibility as a function of vibration frequency. Center curve is mean vibration amplitude; top and bottom curves are ±1 standard deviation. (from Boff & Lincoln, 1988)

The research on whole-body vibration provides an important source of data on the effects that postural perturbations in an aircraft have on vision and manual control (Griffin & Lewis, 1978). Research on vibration and display perception, in particular, provides an experimental paradigm that can be adapted to assess the functional efficacy of postural skills with respect to visual and manual tasks that are characteristic of Shuttle reentry and landing. Such tasks are different than the tasks in which most of the data have been collected in the research on whole-body vibration. Visual tasks in the vibration research generally involve unitary foveal displays while visual tasks in the Shuttle involve multiple displays that are distributed over a wide field of view. Other research has evaluated visual performance with multiple foveal and parafoveal displays, albeit without whole body vibration (see e.g., Wickens, 1986). These studies show that attentional workload increases and visual performance decreases with respect to each display as the number of displays increases. Thus the effects of postural perturbations in the complex environment of the cockpit should be expected to be more severe than in research on whole-body vibration. Multiple displays generally require a larger field-of-view over which information can be picked up by the human visual system. This adds another difficulty insofar as visual performance decreases as the retinal eccentricity of displays increases (Allen, Clement, & Jex, 1970; Moss, 1964). The decrease in visual performance is attributed mostly to the loss of visual resolution with increasing retinal eccentricity and, the loss in visual resolution can be modeled as a decrease in the *signal-to-noise ratio* for the parameter that is monitored in the parafoveal display (Levison, Elkin, & Ward, 1971). This is noteworthy because the visual effects of vibration also can be modeled as a reduction in the signal-to-noise ratio for task-dependent parameters that are visually displayed (Zacharias & Levison, 1979). Thus, *the effects of retinal eccentricity and vibration are commensurable*. The research on whole-body vibration can be adapted, by including tasks that are typical of the Shuttle cockpit, to develop a mature paradigm for evaluating human performance during Shuttle reentry and landing.

Effects of vertical perturbations on visual performance are greater when the task requires maintenance of the point of regard on an object in the near field than when the task simply requires maintenance of the direction of gaze (Moseley and Griffin, 1986; Wilson, 1974). The effects of vertical perturbations on visual performance are influenced by the magnitude and frequency of the perturbations (Figs. 7-10). Effects also are influenced by the size and contrast of the task-relevant optical detail as in any visual acuity task (Figs. 9 and 10; Furness, 1981; Lewis and Griffin, 1979). Significant impairments in visual performance have been observed at vertical seat accelerations as low as 0.25 g and for frequencies of seat vibrations below 10 Hz (Moseley and Griffin, 1986). Effects on visual performance are greater for combined horizontal and vertical perturbations than for vertical alone (See Fig. 9; Meddick and Griffin, 1976). This is noteworthy because there are multiaxis perturbations during vehicular motion. Other features known to interact with visual performance include spatial frequency and luminance contrast. Whole-body vertical vibration increases contrast thresholds for sinusoidal grating patterns by an increasing proportion as spatial frequency of the grating increases. In identical vibration conditions, the largest number of reading errors in a reading task occurs with characters that have the largest amounts of high-spatial-frequency information (Fig. 11). Display legibility increases as luminance contrast increases for low and moderate contrast levels. However, very high values of luminance contrast may degrade the legibility of displays viewed in a vibration environment (Fig. 12).

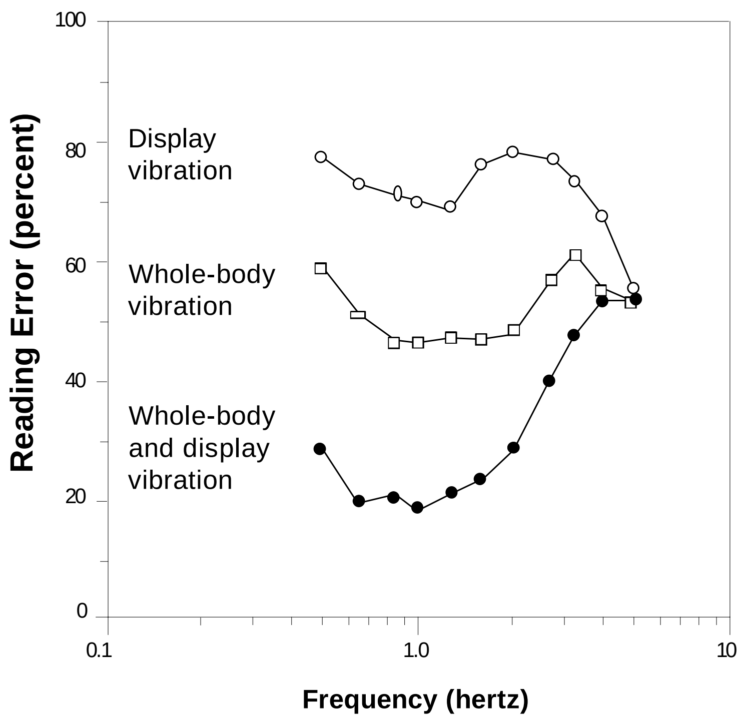

Figure 7. Reading error for three display viewing conditions, 0.5-5 Hz. (from Boff & Lincoln, 1988)

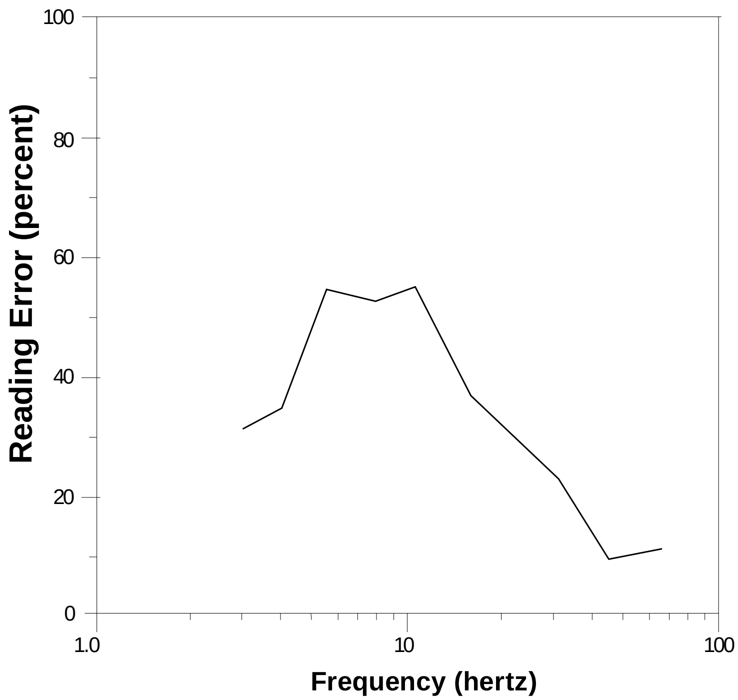

Figure 8. Reading error: whole-body vibration, 2.8-63 Hz. (from Boff & Lincoln, 1988)

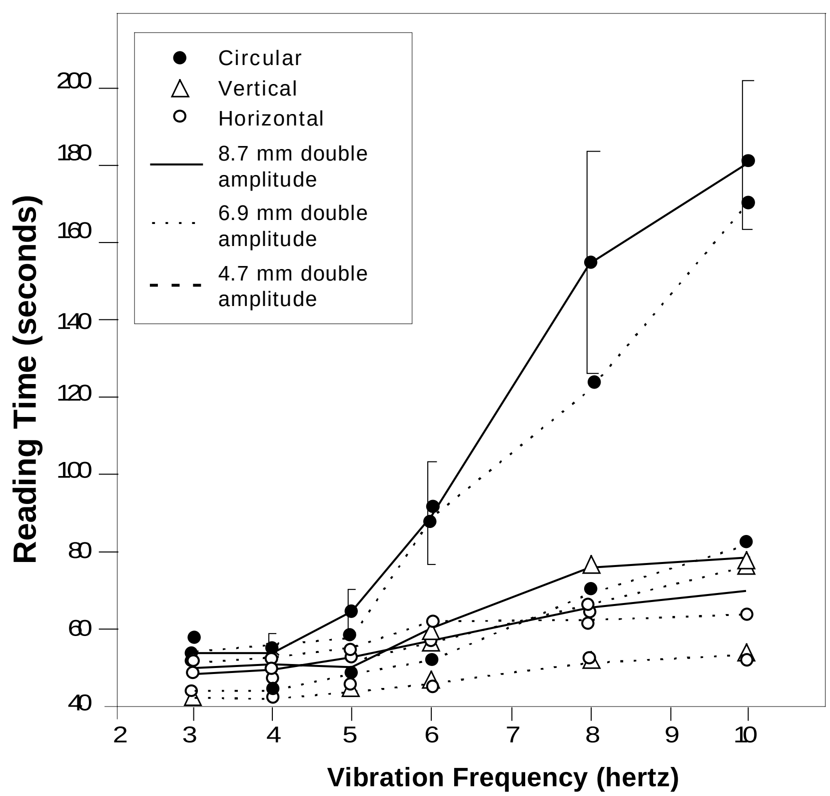

Figure 9. Effect of vertical, horizontal, and dual axis (circular) vibration on visual performance. (from Boff & Lincoln, 1988)

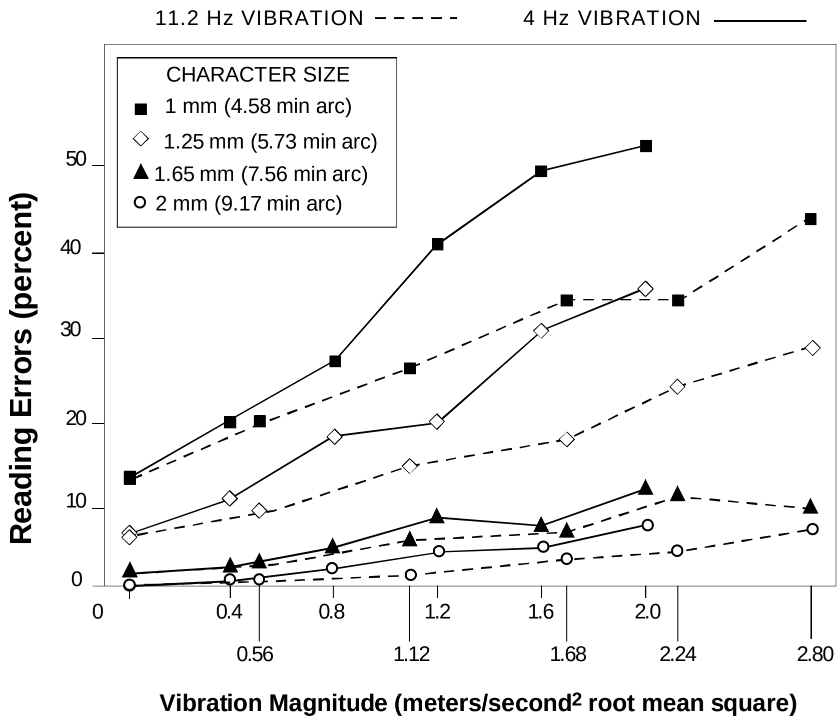

Figure 10. Increase in mean reading error with vibration magnitude for four character sizes. (from Boff & Lincoln, 1988)

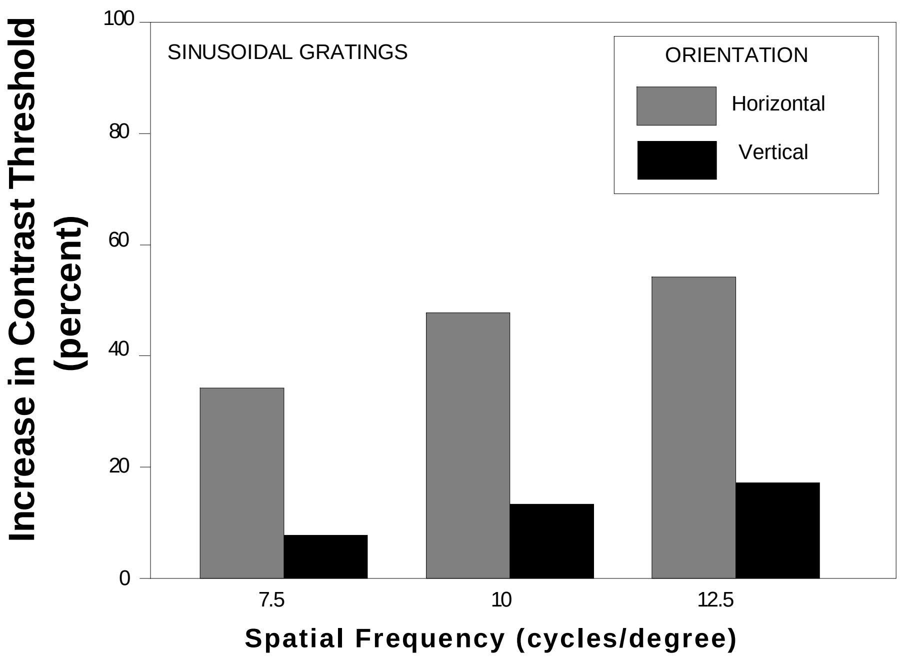

Figure 11. Effect of whole-body vertical vibration on contrast threshold for sinusoidal gratings with spatial frequencies of 7.5, 10, and 12.5 cycles/deg. (from Boff & Lincoln, 1988)

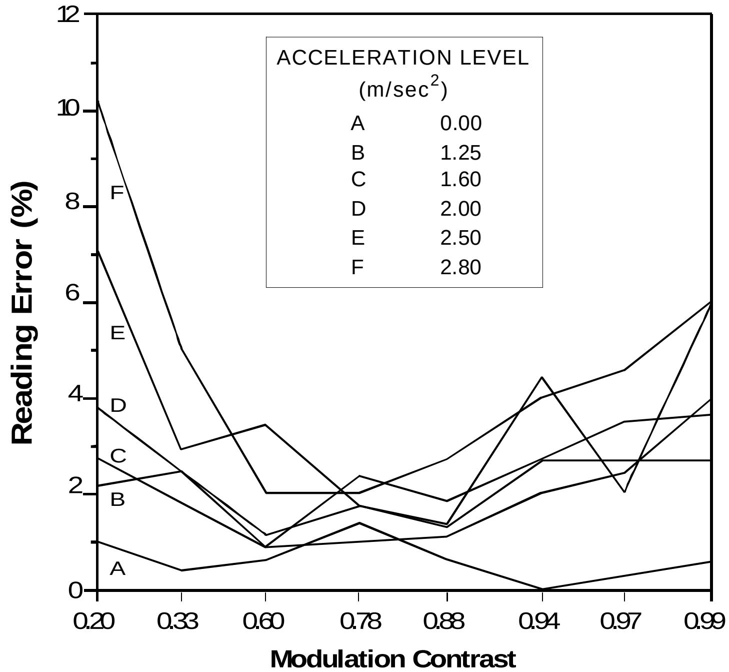

Figure 12. Effect of modulation contrast on reading errors with panel-mounted displays. (from Boff & Lincoln, 1988)

As stated above, manual control is also susceptible to vibration interference. Manual tracking is most sensitive to disruption by whole-body vibration in the region of 3-8 Hz (Fig. 13). Sensitivity of a task to disruption depends upon both system dynamics and vibration frequency content. Dynamics with a simple gain (zero-order dynamics) transmit all frequencies equally. Direct transmission of vibration through the body and into the control system (breakthrough) therefore contributes a large proportion of error in zero-order systems. Dynamics with pure integration (first-order dynamics) attenuate in inverse proportion to frequency. First-order tasks are therefore less sensitive to direct breakthrough. However, first-order tasks are more sensitive to other forms of vibration-induced disruption. It should be noted that translational body motion can induce considerable rotary motion at the controlling limb; rotary knobs can therefore show as much breakthrough as joysticks (see Boff & Lincoln, 1988, for details).

Measurement of visual and manual performance in the Shuttle flight deck would provide a unique opportunity to obtain a quantitative and meaningful evaluation of the *functional consequences* of vehicular vibration and adaptive coordination in the eye-head-torso-hand system.

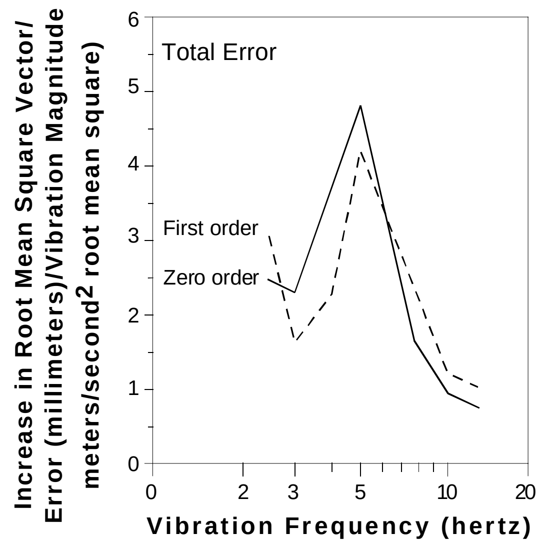

Figure 13. Increase in root mean square tracking error/vibration acceleration level observed during z-axis whole-body vibration. Total static error = 7 mm rms for zero-order dynamics and 15 mm rms for first-order dynamics. (from Boff & Lincoln, 1988)

3.2 Human Performance Adaptations to Weightlessness

There is a clear need for stable visual and manual control during flight deck operations. However, we have data which show that stable visual performance is compromised following short- and long-duration flight. In ongoing investigations of gaze stability while walking on a treadmill, crew members have consistently reported increased oscillopsia (movement of the visual world) following flight while fixating gaze on a target 30 cm from their eyes (Bloomberg et al., 1997). We have also detected changes in eye-head-trunk coordination in this same task. *Space flight adaptation appears to disrupt the compensatory synergy of the eye-head-trunk which together act to maintain stable gaze* under conditions of vertical trunk motion (with each step) and head vibration (Bloomberg et al., 1997).

We have recently extended this investigation to include an evaluation of dynamic visual acuity following long-duration flight. This task entails walking and running on a treadmill while reading back numbers displayed on a computer screen. We have clear evidence indicating that performance following flight is decreased (Fig. 14). We consider this task analogous to reading under vibratory conditions since the interaction with the support surface causes vibration of the head, especially around heel strike. Usually the body acts to attenuate this vibration. However, we have reason to believe adaptation to weightlessness also causes changes in this capacity (McDonald et al., 1997). The data in Figure 15 suggest this may well be true. Figure 15 presents the ratio of the peak axial head acceleration, measured within 100 ms of heel strike, to the initial foot contact ground reaction force peak. Note that the ratio tends to increase, suggesting relatively greater head acceleration postflight.

While we have measured these changes postflight, often several hours or even days after crew members have returned to earth, crew members begin to experience these adaptive changes during reentry. Indeed, we fully expect the response to be even more severe than that observed after landing. Given such changes, the ability to deal with mechanical disturbances, and the ability to control visual and manual stability during reentry and landing will be compromised.

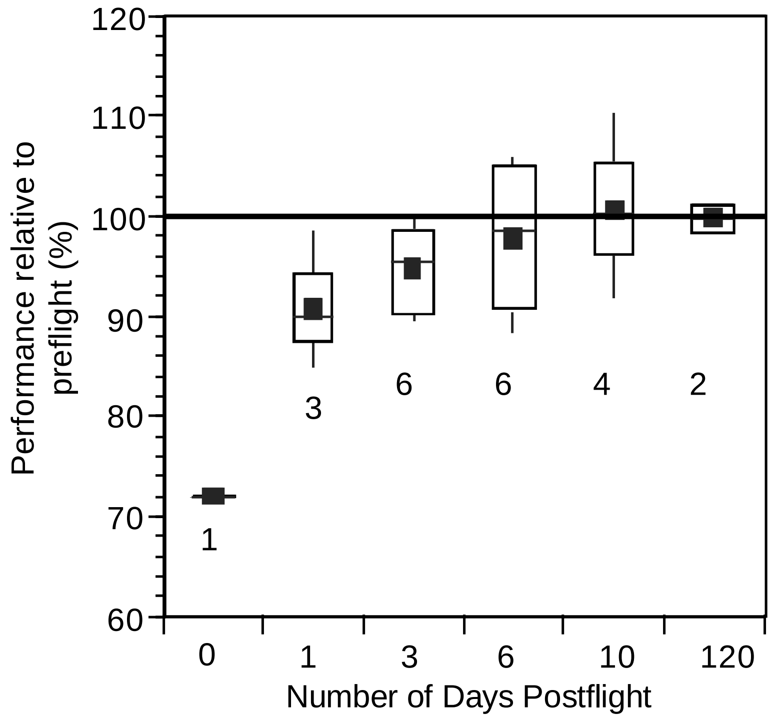

Figure 14. Postflight dynamic visual acuity performance presented as a percentage of preflight performance after long-duration flight. Numbers under each box indicate the number of subjects.

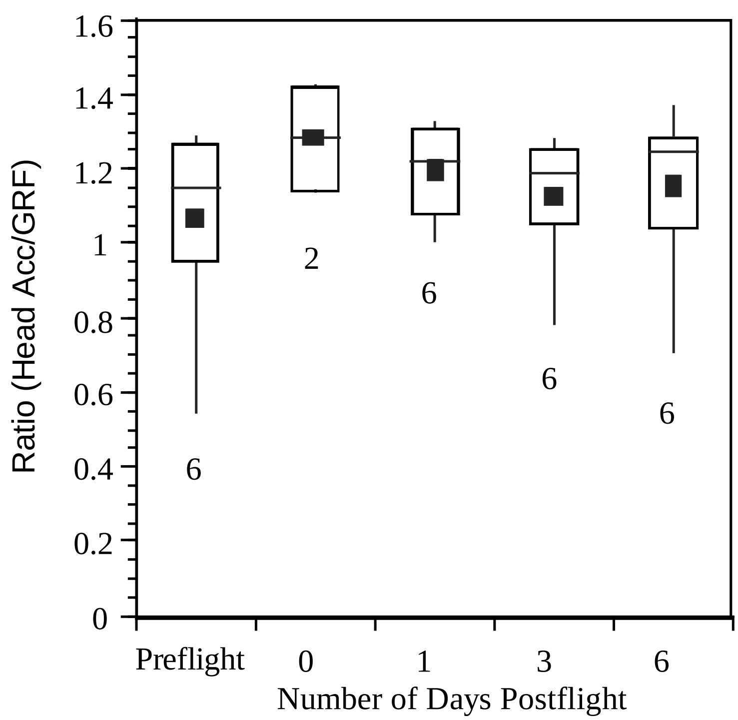

Figure 15. Ratio of axial head acceleration to the initial foot contact ground reaction force peak before and after long-duration flight. Numbers under each box indicate the number of subjects.

Further evidence for disruptions in oculomotor coordination as a result of spaceflight is found in studies of the vestibulo-ocular reflex (VOR). The VOR is used in the generation of compensatory eye movements during head rotation. The VOR operates so that, during head movements, gaze can be stabilized permitting fixation on the desired location. Evidence to date indicates that the coordination between head and eye is modified by exposure to weightlessness both during target acquisition (see Reschke, 1994, for a summary), ocular saccadic activities (Uri et al., 1989), and pursuit tracking (Kornilova et al., 1991). These data are consistent with the note that is included in the Shuttle Crew Operations Manual which suggests:

> When returning from orbit, crew members should be aware of the potential for some change in the vestibular sensations. Head movements will tend to make these changes more noticeable. Flight crew members should avoid exaggerated head movements during landing to reduce the possibility of disorientation. (p. 7.4-24)

Crew members flying aboard the SLS-1 mission participated in an investigation of preflight, inflight, and postflight limb positioning ability (Young et al., 1993). Subjects, with their eyes closed, were required to point at five remembered targets. While preflight pointing in the absence of vision was highly accurate, performance was clearly degraded both during and immediately after flight. Inflight, two subjects who were very accurate preflight, showed a pointing bias predominantly toward the floor. After two subjects made several errors when trying to touch various body parts, they noted that their arms were not where they expected them to be when their eyes were open both during and after flight. While one may prefer to look where one is pointing/reaching, the physical layout of the Shuttle flight displays and controls does not always permit this preference.

Manual activities during Shuttle operation require more than simple pointing tasks. More often than not a prehensile component is necessary while flicking a switch or adjusting a knob. It appears that this prehensile capacity may also be compromised during unusual inertial conditions. Recent data on grasping of virtual objects in altered gravity indicated that the final grip aperture was 15% smaller than in normal 1g, and the peak grip aperture was 30% less affected by target size. These findings were consistent in both hyper- and micro-g (Bock, 1996).

In summary, this evidence indicates the human capacity for accurate and reliable visual and manual control is compromised under the conditions experienced during Shuttle ascent, reentry, and landing. The nature of these changes in performance should be exploited in determining design specifications for future cockpit displays and controls.

4. Multicriterion Control and Coordination in Nested Systems

This section lays out the theoretical foundation for the interpretation of the material discussed thus far in the context of advanced cockpit design. A more complete exposition of this theoretical orientation is presented in Part I of this series[1].

4.1 Theoretical Foundations

There are important consequences of mobility and flexibility of the pilot in the aircraft. On the one hand, movements of the pilot that are due to vehicular motion can provide information for vehicular control.

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[1] Riccio, G.E. & McDonald, P.V. (1998). Multimodal Perception and Multicriterion Control of Nested Systems: I. Coordination of Postural Control and Vehicular Control.

On the other hand, uncontrolled movements of the body can interfere with perception and action in the cockpit. If uncontrolled movements interfere with vehicular control, reduction of uncontrolled movements should improve vehicular control. One method of reducing uncontrolled movements is to reduce mobility and flexibility of the pilot by adding passive restraints in the cockpit. For example, adding shoulder restraint pads to the conventional lap belt and shoulder harness in the cockpit of a high-performance vehicle improves tracking performance when the pilot is subjected to sustained or fluctuating lateral forces that are due to vehicular motion (Van Patten, Repperger, Hudsen, & Frazier, 1983). Reduction of uncontrolled movements through such a system of passive restraints improves both the precision and accuracy of control; fewer control errors are made and there is less cross-coupling among the various degrees of freedom (DOF) in the multi-input multi-output control that is typical of flight.

The pilot, and other occupants of a vehicle, also reduce uncontrolled movements through adaptive postural control activity. The various segments of the body must be actively stabilized whenever one is not passively stabilized (Riccio & Stoffregen, 1990; Stoffregen & Riccio, 1988). Even when it is reasonable to maximize passive restraints on the torso (e.g., in a vehicle), it is important to allow some mobility of the head and limbs to facilitate looking at, around, and through; and to facilitate reaching and manual control (Riccio et al., 1998; Riccio & Stoffregen, 1988). Mobility can be increased through reduction of passive restraint, but this also increases the demands on active stabilization, that is, on postural control. Postural control with various body segments is limited by passive restraints such as seat belts and shoulder harnesses. Pushing on support surfaces with the legs and arms can be used to compensate for torques due to tilt or imbalance (cf., Riccio & Stoffregen, 1988; Zacharkow, 1988), but such postural control strategies can lead to inappropriate actions on the control stick and rudder pedals (Van Patten et al., 1983). In an aircraft cockpit, the major body segments that can be coordinated in this way are the head and the upper torso (Riccio, 1995; Riccio et al., 1998).

The dynamics of balance in the cockpit vary because of variation in the gravitoinertial vector within and across typical flight maneuvers (see e.g., Brown et al., 1991; Riccio, 1995; Riccio et al., 1998). Linear and centripetal acceleration of the aircraft change both the direction and magnitude of the gravitoinertial vector. Changes in the direction of this vector shift the location of the potential gradient for balance in the postural configuration space. Changes in the magnitude of this vector change the steepness of the gradient and change the size of the region within which postural perturbations can be reversed. Thus, postural control in vehicles must be robust, or it must adapt, to variations in both the direction of balance and the consequences of imbalance. Postural aftereffects of exposure to altered gravitoinertial environments have been demonstrated in several investigations using human centrifuges (Bles & de Graaf, 1992; Hamilton, Kantor, & Magee, 1989; Martin & Riccio, 1993). These studies reveal that limits on adaptability vary among individuals and that, beyond these limits, individuals experience postural instability and motion sickness. In some cases, stability limits are avoided by adopting robust postural control strategies characterized by stiff, “robot-like,” or other movement patterns with reduced DOF.

Adaptability is also important because the evaluation functions, and associated potential gradients, for postural control are influenced by situation-specific factors other than torques on the body segments (Riccio, 1993; Riccio & Stoffregen, 1988; 1991). Such factors include different constraints which are imposed on postural control by different tasks. We have shown that postural perturbations are different for tasks involving reading, low-force tapping, or simply maintaining balance when the mechanical conditions are otherwise identical (Riccio, Lee, & Martin, 1993). These results also suggest that task constraints can have effects that are similar to the effects of mechanical constraints, and these constraints can be modeled in the similar ways. In particular, movement of the head due to whole-body perturbation was reduced for the reading task while movement of other body segments was unaffected. Thus, adaptation of multisegment (i.e., nonrigid) postural control to task constraints was both specific and functional. In many cases, such coordination requires exquisite observability and controllability of the interaction between translation and rotation of the head. Given that prolonged weightlessness alters vestibular perception of translation and rotation, we suspect that space flight adaptation may result in head-trunk coordination that is less specific and less functional given the task demands of reentry.

The meaning of the sensory information, its implications for action, is influenced by the context. For example, perceived rotational motion or change in orientation may or may not require a compensatory postural action. Disturbances on the aircraft can result in changes in orientation (e.g., pitch and roll) of the aircraft that may not be visible if outside-the-cockpit optical structure is impoverished. In addition, the visible surroundings inside the cockpits of many aircraft are often more extensive and richer in optical structure than the visible surroundings outside the cockpit, and the visible surroundings inside the cockpit are more relevant to perception and action in the cockpit (e.g., viewing instruments and handling controls). Furthermore, the support surfaces move with the visible surroundings inside the cockpit. This presents a problem for postural control that may be difficult to overcome: *Posture may be controlled with respect to the support surfaces and visible surroundings inside the cockpit to facilitate interaction with the cockpit environment, but posture must also be controlled with respect to the inertial environment to avoid or limit imbalance* (note that this is a problem even when the surroundings outside the cockpit are visible). This situation is analogous to “sway referencing” of the support surface and visible surroundings during the experimental or diagnostic evaluation of stance (see Nashner & McCollum, 1985). It is well known that vestibular sensitivity to imbalance mitigates the destabilizing effects of these unusual environments. We suspect that space flight adaptation may result in difficulties with perception and action in the cockpit over changes in the g-vector and over the complex relationships among sensory reference frames during reentry.

4.2 Relevance to Flight Deck Performance

4.2.1 Task Constraints

The adaptability and sensitivity of postural control must be considered with specific reference to (nonmechanical) task constraints imposed in particular phases of the mission. Only under these circumstances could this information indicate whether visual and manual stability is governed by tacit knowledge of the effects that head and trunk motion has on visual and manual performance (Riccio, 1993, 1995; Riccio et al., 1998; Riccio & Stoffregen, 1988, 1991). Individual differences due to experience in postural stabilization and in performance under challenging cockpit conditions also shed light on these aspects of piloting skill. As noted above, everything from postural control in the cockpit to looking and reaching patterns must be considered as part of a pilot's skill. This skill allows a pilot to perform effectively in the visually and mechanically complex aerospace environment. Adaptability is an essential aspect of such whole-body skills, and it allows a pilot to perform adequately even in novel or unusual circumstances. The design of controls and displays and the development of flight-control procedures takes into account, explicitly or implicitly, such skill and adaptability. Planning for new environments or emergency situations is greatly facilitated by a technical understanding of the limits of human skill and adaptability.

4.2.2 Whole-Body Perturbations

There is a conspicuous lack of detail in descriptions of the vibration environment, including the resulting postural perturbations, on the Shuttle flight deck during reentry. Data were collected on early Shuttle flights, but were directed more to evaluating structural integrity of the flight deck and instrumentation. Little or no attention appears to have been given to the human performance implications of these vibrations. From the material we have reviewed it is clear that the relation between motion of the crew members' head, trunk, and seat is critical for preserving robust visual and manual control. Moreover, each phase of a mission presents different challenges to preserving this control. Specifically, attention must be given to the context specific performance:

- during predictable and unpredictable disturbances
- during ascent/abort performance
- during reentry/landing performance
- for different types and axes of disturbances
- for different body configurations (e.g. head up vs. head down)

Evaluations of performance in these contexts will provide detailed information about postural perturbations during vehicular disturbances that are typical of abort, entry and landing. Such data will be useful in future applications of human performance models to advanced cockpit design.

4.2.3 Visual/Manual Performance

Measurement of visual and manual performance provides a unique opportunity to obtain a quantitative and meaningful evaluation of the functional consequences of vehicular vibration and adaptive coordination in the eye-head-torso-hand system. On the basis of the material reviewed here, one would expect that there will be significant impairments in visual and manual performance under conditions of whole-body perturbations that are common during Shuttle ascent and reentry. Visual performance should decrease with increases in the RMS magnitude of disturbances in all translational and rotational axes. Uncorrelated disturbances in multiple axes will have a significantly greater effect on visual performance. Visual performance should increase with increases in modal frequency of disturbance power between 1 and 10 Hz. Below 5 Hz, the effect of the disturbance spectrum on visual performance should be influenced by the known dynamics of the vestibulo-ocular reflex. As indicated in Section 3.1, manual control is also susceptible to vibration interference. We expect that the greatest disruption in manual tracking will occur for whole-body vibration in the region of 3-8 Hz. The frequency dependence of effects on visual performance and manual control should be different for different types and axes of disturbance because of the dynamics and adaptability of shock absorption for the corresponding body axes. Predictability of disturbances should reduce the effects of disturbances, and this interaction should be frequency dependent.

The specification of the disturbance profile and associated human response capabilities will determine the robustness of human performance in the cockpit. The consequences of such relate directly to handling qualities and flight control (see e.g., Riccio, 1995; Riccio et al., 1998). Indicators of potential problems include time delays, spatial errors such as overshoot, PIOs, damped oscillations of the simulated vehicle that suggest imminent PIOs, and degraded visual performance that can lead to such problems with spatiotemporal accuracy and precision. It is necessary to identify, by direct observation or extrapolation, the magnitudes of perturbation that lead to delayed or inaccurate responses. Such boundaries can be specified for particular axes and for particular combinations of axes. Soft or fuzzy boundaries can be represented, for example, in gradients implicit in nested iso-performance contours in joint parameter spaces (Riccio, 1993, 1995; Riccio et al., 1998; Stoffregen and Riccio, 1988, 1991). The key is to identify regions where degradation in handling qualities and flight-control performance is highly nonlinear or "explosive" over smooth changes in parameters of the pilot-vehicle system. The resulting relationships describe the domain of perturbations within which visual perception and manual control are sufficiently robust to allow for stable flight control and acceptable handling qualities.

4.2.4 Coordination of Nested Systems

We are convinced that it is crucial to gather quantitative information about the effects of stability and adaptability of whole-body coordination on display perception within the flight deck context. In this context, we would expect to see a monotonic yet nonlinear relationship between reading accuracy and the departure from unity-gain negative-feedback compensation for the head-neck system. Relatedly, we would expect to observe a two-dimensional "tolerance region" (Riccio and Stoffregen, 1988, 1991) with respect to unity gain and 180° phase relations for the head-neck system, within which there will be no effect of imperfect compensation on performance. Such tolerance should be provided by oculomotor compensation and by attentional mechanisms that facilitate visual perception during expected changes in retinal projection of the display. Outside of this tolerance region, we would expect to observe sharp decrements in performance due to excessive blurring of the retinal image (Boff and Lincoln, 1988). Retinal blur and decrements in display perception have been observed with whole-body accelerations below 1 g (see Section 3.1). Retinal blur and the effects on visual perception would be exacerbated by any aftereffects of weightlessness on oculomotor compensation (see Section 3.2). Postural perturbations due to vehicular vibration and aftereffects of weightlessness each pose challenges to oculomotor compensation. A better understanding of these challenges can lead to the design of more robust displays and to training methods or other prophylactic measures that enhance visual perception and performance in the cockpit.

Measurement of perceptual performance in these operationally relevant conditions provides a unique opportunity to obtain a quantitative and meaningful evaluation of departures from unity gain and 180° phase relations in the head-neck system. More generally, it provides a meaningful evaluation of the task constraints that is commensurate with the evaluation of mechanical constraints. As indicated in Section 4.0, posture may be controlled with respect to the support surfaces and visible surroundings inside the cockpit to facilitate interaction with the cockpit environment, but posture must also be controlled with respect to the inertial environment to avoid or limit imbalance. In dynamical models of purposeful movement systems, evaluative functions that include such effects of movement and performance are as important as the classical functions associated with energy management (Riccio 1993, 1995; Riccio et al., 1993; Riccio et al., 1998). Such understanding of postural dynamics and the skills involved in human-systems interaction provides a firm foundation for recommendations about interface design and about training that fosters the development of the associated whole-body skills. It increases the range of scientific knowledge that is recognized as operationally relevant and, thus, that can be applied to advanced cockpit design.

5. Cockpit Design Implications

5.1 Robustness of Cockpit Displays and Controls

Impaired visual performance may arise from the vibration of the eye induced by whole-body vibration or by vibration of the object or displays being viewed. The effects of vibration on vision depends on many factors including viewing distance, the translation and rotation components of ocular disturbances, and luminance adaptation (Casagrande, et al., 1986; Irvin, Norton & Casagrande, 1986; Irvin & Verrillo, 1979; Verrillo & Irvin, 1979). The state of luminance adaptation of the visual system determines the temporal integration constant of the visual system and, hence, the spatio-temporal frequency effects of vibration on retinal blur (Kuyk, et al., 1983; Irvin, et al., 1983). Consequently quantification of the spatial characteristics of cockpit displays is critical for any accurate determination of human performance limits. These spatial characteristics include spatial frequency analysis and characterization of information-relevant aspects of display elements such as length of bar indicators, orientation of pointers, visual subtense and spacing of alphanumeric, luminance contrast, and line width. It is our position that relevant display elements should be spatially characterized according to their critical features for visibility and in a manner which facilitates the quantification of vibration effects on visibility. As a result the effects of vibration on the display characteristics can be represented as perturbations in spatio-temporal frequency and variations in contrast.

The spatio-temporal contrast sensitivity characteristics of the human visual system and, hence, vibration-induced degradation of visibility depend critically on the state of visual adaptation due to mean illumination. Mean illumination of the cockpit displays under operational conditions provides the appropriate spatio-temporal characterization of visual display features over specified perturbations of the head. The quantification of the relevant spatial characteristics of cockpit displays and the effects of vibration on the appropriate space, time, and intensity properties of the critical display features will enable appropriate metrics of display visibility to be applied under representative vibration and illumination conditions in the cockpit. Our approach provides a relevant and common representation for display features and vibration effects. This in turn facilitates a quantitative assessment of the visibility of extant display elements and display systems with respect to representative vibration conditions (Doyal, Irvin, Donohue, & Dowler, 1992; Doyal, Irvin & Ramer, 1995; Irvin, Gaska, & Jacobson, 1995; Stengle et al, 1994).

5.2 Robust Cockpit Design

As indicated in Section 3.1, loss in visual resolution can be modeled as a decrease in the signal-to-noise ratio for particular features in a visual display, and the visual effects of vibration also can be modeled as a reduction in the signal-to-noise ratio for task dependent parameters that are visually displayed (Levison, Elkin, & Ward, 1971; Zacharias & Levison, 1979). Section 3.1 also indicated that whole-body perturbations can be described as an illumination-dependent reduction in modulation contrast due to the superposition of a "noise" distribution on the retinal projection of a display. Knowledge about visual acuity and display characteristics can be applied to identify the domain of gaze instabilities over which there is sufficient acuity for timely and accurate decisions and responses in the cockpit. Challenges to gaze stability and visual acuity, then, can be derived from this information together with data on the whole-body perturbations that would be experienced during abort, entry and landing maneuvers of space vehicles. One should then be able to indicate the extent to which oculomotor compensation is required for adequate performance in the cockpit. This would subsequently allow one to make inferences about the likelihood of vibration-related acuity problems in the cockpit based upon the scientific literature on oculomotor control (see Section 3.2). Analysis of this form will reveal the relative robustness of various extant and planned display elements and display systems with respect to gaze stabilization under challenging conditions in the space vehicles.

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This report reviews the operational demands made of a Shuttle pilot or commander within the context of a proven empirical methodology for describing human sensorimotor performance and whole-body coordination in mechanically and perceptually complex environments. The conclusions of this review pertain to
a) methods for improving our understanding of the psychophysics and biomechanics of visual/manual control and whole-body coordination in space vehicle cockpits.
b) the application of scientific knowledge about human perception and performance in dynamic inertial conditions to the development of technology, procedures, and training for personnel in space vehicle cockpits.
c) recommendations for mitigation of safety and reliability concerns about human performance in space vehicle cockpits.
d) in-flight evaluation of flight crew performance during nominal and off-nominal launch and reentry scenarios.

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